MR Quantification of Flow in Children with Vascular Malformations

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Summary

The evaluation of treatments such as embolization, stereotactic radiation, and even surgery would be enhanced by an objective method of measuring flow in feeding arteries or draining veins.

We developed a non-invasive method of measuring vascular flow using cardiac gated phase contrast MR angiography (MR Q flow).

The purpose of this work was to employ the same technique in a series of patients with vascular malformations of the head and neck. We selected a series of vascular malformations with simple arterial and venous architecture and significantly smaller vessel diameters than that encountered with Vein of Galen Malformations. Our aim was to determine the reproducibility of the derived flow values by using multiple velocity encoded sequences (VENC) and compare the values derived from the arterial feeders to the venous outflow data.

There are inherent technical difficulties with assessing flow through multiple arterial feeders or draining veins, so the technique is most easily applied to AVMs with simple, easily defined feeding arteries or draining veins. Nonetheless, this technique is relatively straightforward to learn, rapid, cost-effective and may provide an objective means to assess therapeutic maneuvers when applied to head and neck vascular malformations.

Introduction

CT angiography (CTA) and MR angiography (MRA) can map out the feeding arteries and draining veins of vascular malformations[1,2], but it is our belief the evaluation of treatments such as embolization, stereotactic radiation, and even surgery would be enhanced by an objective method of measuring flow in feeding arteries or draining veins. Because the angiographic evaluation of a Vein of Galen aneurysmal malformation (VGAM) in an infant is limited by the amount of contrast available for injection and the draining vein is usually large. We developed a non-invasive method of measuring vascular flow using cardiac gated phase contrast MR angiography (MR Q flow)[3] (see also the paper submitted with this one: "MR Quantification of Flow in Children with Vein of Galen Malformations"). The purpose of this work was to employ the same technique in a series of patients with vascular malformations of the head and neck. We selected a series of vascular malformations with simple arterial and venous architecture and significantly smaller vessel diameters than that encountered with Vein of Galen Malformations. Our aim was to determine the reproducibility of the derived flow values by using multiple velocity encoded sequences (VENC) and compare the values derived from the arterial feeders to the venous outflow data. Our goals were to see if

Table 1 **Scan Parameters for VENC studies**

TR	varies with heart rate
TE	2.4-6.6 ms
FLIP ANGLE	30 degrees
FOV	30 or 40 cm
MATRIX	192 x200
PIXEL SIZE	1.6x1.5mm or 2.1x2mm
SLICE THICKNESS	4.7-6.8mm
AVERAGES	2
CARDIAC PHASES	20-45 per cardiac cycle (collected 2 RR intervals)
BANDWIDTH	15.63 KHz
GRADIENTS	27mT/meter & 72 mT/meter/ms shielded power gradients
VENC	50-600 mm/sec (in slice)

the technique was feasible and determine if it could be employed to measure the effect of treatment.

Material and Methods

Five cases have been selected for this report to demonstrate the potential of quantitative MR flow techniques. All velocity encoded (VENC) MR studies were carried out on a Picker 1.5 T HPQ or Edge system (Picker Int'l. Cleveland, Ohio) with a standard cardiac software package using prospective ECG gating. Validation of all flow sequences using flow phantoms was performed as part of our initial testing before the validated sequences were applied to children with vascular malformations [3].

MR studies included routine sequences and 3D ToF MOTSA MRA. Imaging included axial, sagittal and/or coronal T1 weighted images 600/20/2/192x256, (TR/TE/AV/MATRIX SIZE), axial spin echo or fast spin echo T2 weighted images (2500-3500/40, 80/ 1-3/192x256) and a 3DT1 weighted sequence (24/4.4/2 mm/256x256). Incoherent gradient echo MRA sequences, (SPGR or RF-FAST) were usually placed in a transverse plane with or without a presaturation pulse. If a presat pulse was selected, the parameters were 42/6.9/20/20/0.9/180x180 (TR/TE/FOV/FLIP ANGLE/THICKNESS/ MATRIX SIZE). The sequence included MTC (B1=800 Hz) at an offset of 2500 Hz, [4] and imaging times ranged between 10 and 12 minutes.

Either the MRA or the standard images were used to place velocity sensitive sequences (MR Q Flow) perpendicular to the arterial input or venous outflow of the vascular malformation. These were incoherent gradient echo sequences (GRASS or FAST) with motion artifact suppression. Flow rates ranged from 50-600 cm/s, and velocity sensitivity was run in the slice select plane. Additional parameters are outlined in table 1. Multiple VENC sequences were performed and an adequate data set was obtained when the slowest available flow sensitive sequence did not alias.

The flow data was analyzed with the provided cardiac software package by generating flow maps across the cardiac cycle and using the flow maps and corresponding magnitude images to trace anatomic regions of interest (ROI). Once the ROI's were created, the software calculated peak velocity, average flow rates per duty cycle (30-40 msec) and average flow rates per second. Arterial flow rates were determined by adding the flow rates /duty cycle because of marked variation in flow during systole and diastole. All flow values were finally

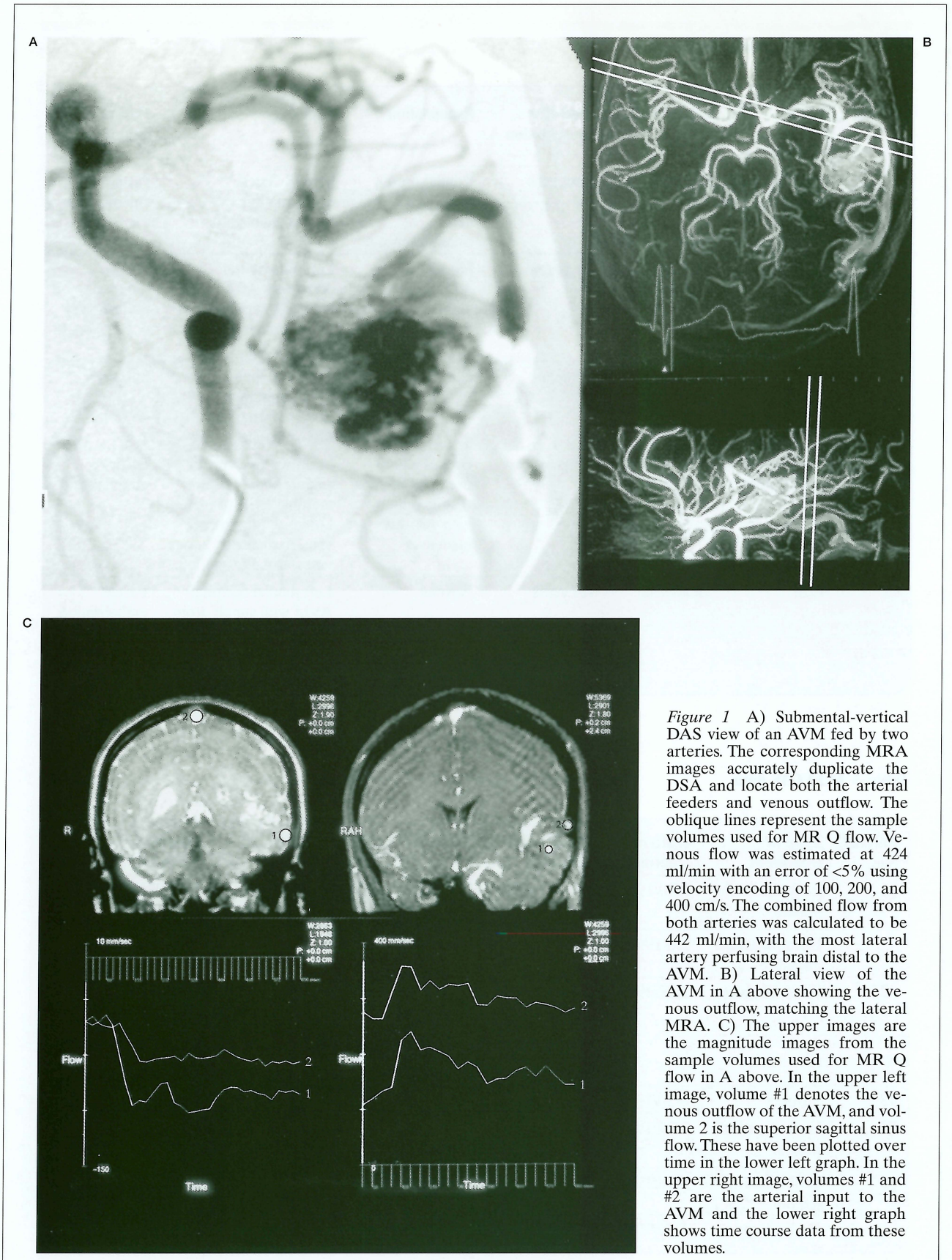


Figure 1 A) Submental-vertical DAS view of an AVM fed by two arteries. The corresponding MRA images accurately duplicate the DSA and locate both the arterial feeders and venous outflow. The oblique lines represent the sample volumes used for MR Q flow. Venous flow was estimated at 424 ml/min with an error of <5% using velocity encoding of 100, 200, and 400 cm/s. The combined flow from both arteries was calculated to be 442 ml/min, with the most lateral artery perfusing brain distal to the AVM. B) Lateral view of the AVM in A above showing the venous outflow, matching the lateral MRA. C) The upper images are the magnitude images from the sample volumes used for MR Q flow in A above. In the upper left image, volume #1 denotes the venous outflow of the AVM, and volume 2 is the superior sagittal sinus flow. These have been plotted over time in the lower left graph. In the upper right image, volumes #1 and #2 are the arterial input to the AVM and the lower right graph shows time course data from these volumes.

Table 2 **Patient characteristics**

Patient	Type of vascular malformation	Presentation	Age of presentation	Examination	Radiology	Type of treatment
#1	Vein of Galen malformation	Seizure	4 months	Cranial bruit, Increasing head circumference	Vein of Galen malformation Ventriculomegaly	Partial embolization x 2
#2	AVM	Hemorrhage, Hydrocephalus	11 years	Mild RLE weakness	Left parasagittal AVM with ACA and PCA supply. Single draining vein into SSS.	EVD, Linac radiosurgery
#3	AVM	Seizure	15 years	Normal	Temporal lobe AVM near apex of sylvian triangle. MCA feeding vessels.	Surgery
#4	Facial vascular malformation	Bruit, Facial asymmetry	15 years	Bruit, Fullness over right zygoma that increased with valsalva maneuver	Scalp AV fistula with arterial supply from multiple ECA branches. Drainage into int. jug vein. Associated venous vascular malformation.	Partial embolization
#5	AVM	Headache	14 years	Normal	Left medial occipital AVM with supply from PCA brs. Venous drainage is deep (Galen) and superficial (SSS).	Partial embolization, Linac radiosurgery

Table 3 **Q FLOW data**

Patient No.	Type of treatment	Date of treatment	Radiologic followup	Date	MR flow (cc/min)	MR flow (cc/min)
#1	Embolization–partial	9/20/1994	Pre-treatment	8/16/1994	1800 (cardiac output)	993 (straight sinus)
			0.48	3/14/1995	1486	328
	Embolization–partial	7/6/1995	1.12	11/3/1995	2350	15
#2	Radiosurgery	1/22/1997	0.42	6/24/1997	146	152
			0.67	9/23/1997	162	20
			1.12	3/6/1998	160	4
			2.03	2/2/1999		No vein identified
#3	Surgery	6/20/1997	Pre-treatment	6/16/1997	442	424
#4	Embolization–partial	7/28/1997	Pre-treatment	7/25/1997	150 (Rt ECA-LtECA)	153
			0.41	12/23/1997	14 (Rt ECA-Lt ECA)	41
#5	Embolization–partial	8/18/1998	Pre-treatment	3/19/1998	Not done	110
	Radiosurgery	1/21/1999				

expressed in ml/min. The values derived from the slowest velocity sensitive sequence without aliasing were defined as the most reliable data. Comparison among the available sequences was carried out and expressed as a per cent variation.

Parts of the method are illustrated in figure 1.

Patients selected for MR Q Flow had both CT and angiography performed as part of their investigations. The CT and CTA studies were performed on a Siemens Somatom Plus scanner (Siemens, Iselin N.J.) Routine imaging consisted of contiguous axial 5 mm slices obtained at 20 degrees from the canthomeatal line. CTA was performed as 2 mm dynamically acquired images following the injection of contrast. Standard CT software was used for 3D image display. All angiographic studies were performed on a Siemens Polytron S/Plus DSA unit.

Patient characteristics are summarized in table 2 and Q flow data are summarized in table 3.

Patient 1:

A male infant presented with seizures and a large head at the age of four months. CT, MRI and angiography all demonstrated a Vein of Galen Aneurysmal Malformation (VGAM). Baseline MR Q flow studies were performed at the time of diagnostic MR study using the technique outlined above. Venous samples were obtained perpendicular to the medial vein of the prosencephalon (embryological precursor of the straight sinus) using velocity encoding of 200 and 400 cm/s. Cardiac output was measured by sampling across the ascending aorta using the same velocity encoded sequences. Data was acquired across two RR intervals because of expected high flow rates in diastole. One complete cardiac cycle was employed to calculate the true flow rates.

At diagnosis the AVM flow rate was estimated to be 1000 ml/min., with both VENC studies agreeing within 1%, or 7 ml/min. Total systemic cardiac output was calculated at 800 ml/min. and the shunt fraction expressed as a per cent of cardiac output was 55%.

The VGAM was embolized at five months of age and the MR Q flow study was repeated seven months later because MR demonstrated a persistent VGAM. VENC sequences of 100 and 200 cm/s were employed and estimated the residual venous flow at 329 ml/min and 326 ml/min. The shunt flow was estimated at 22% of cardiac output while total systemic cardiac output had increased to 1160 ml/min. The patient was re-embolized within one month of the MR study and the angiogram confirmed that a significant shunt was still present.

The child was re-examined at 20 months of age. MRA showed minimal residual flow within the straight sinus and did not detect any abnormal arterial feeders. Venous flow was measured using VENC sequences of 50, 100 and 200 cm/s and the residual flow was calculated at 15-20 ml/min, or less than one per cent of cardiac output. Systemic cardiac output was calculated at 2335 ml/min or 163 ml/min/kg. Angiography confirmed elimination of the VGAM and the persistent residual flow in the straight sinus. Repeat MR study at 38 months ultimately showed flow at <2.

Patient 2:

An eleven-year-old male presented with a spontaneous intracerebral hemorrhage and a diagnostic angiogram demonstrated a left sided medial hemispheric AVM supplied by two arterial feeders and drained by a single vein. The patient required temporary external ventricular drainage and made a good neurological recovery. The AVM nidus measured 1.8 cm and it was elected to treat the AVM with stereotactic radiation.

MR Q flow studies were not obtained until five months after radio-surgery and we have assumed these flow values are representative of the baseline flows at the time of treatment. The localizing MRA was identical to the pre-treatment MRA in demonstrating the signal intensity and architecture of the arterial feeders, nidus and draining vein. Multiple velocity encoded trials were run sampling both the arterial feeders and venous outflow using VENC of 50,100 and 200 cm/s.

The diameters of the sampled vessels were small. The diameter of the vein measured between 2.5 and 3 mm. compared to the arteries which were measured between 1.4 and 2 mm. Background phase errors were measured at less than 5 ml/min. The venous outflow was calculated to be 155 ml/min with all VENCs agreeing within 5 ml/min, or less than 4%. Arterial estimates ranged from 146-160 ml/min, a variation of less than 8%. Thus the estimated

arterial and venous flows values were within plus or minus 6% of each other.

Eight months after radio-surgery the patient presented with headaches and repeat CT and MR studies showed focal edema surrounding the AVM nidus. The MRA was not significantly different in appearance, but the flow studies were dramatically altered. Venous flows were calculated at 20 and 23 ml/min using velocity encodings of 100 and 200 cm/s. Flow studies were repeated at 1.12 years and 2.03 years after treatment and showed a progressive decrease in flow until no venous flow could be identified. All studies were carried out with a minimum of two to three VENC and the flows varied less than eight per cent. A final angiogram was performed 28 months after radio-surgery and confirmed the elimination of the AVM. Surprisingly, the summed arterial flows were measured on all post radio-surgery studies and maintained a value between 160-162 ml/min.

Patient 3:

A fifteen-year-old female presented with a temporal lobe seizure and an outside CT examination that demonstrated an AVM. A diagnostic angiogram and MR study were performed within one week of each other. The angiogram demonstrated two potential feeding vessels from the left middle cerebral artery. However it was believed that one of the vessels seen best in the submental vertical projection was most likely a vessel of passage and did not contribute to the AVM nidus.

Flow studies were able to sample the draining vein and interrogate both potential feeding arteries using VENC sequences of 100, 200, and 400 cm/s. The diameter of the draining vein was measured between 4.8 and 5 mm, while the arteries were significantly smaller at 2.3 and 2.5 mm. Background phase errors measured less than 8 ml/min in the sample plane. The AVM venous flow was measured at 424 ml/min with all VENC studies agreeing within 2%, or 8 ml/min. The single definite arterial feeder identified on the angiogram had a measured flow rate of 250 ml/min, which was insufficient to account for all of the venous flow. The summed flow rates of both arteries was between 442 and 450 ml/min, (+/- 2%), which was enough to account for the AVM flow and the more distally perfused vascular territory seen on the angiogram. It was concluded that both arteries must contribute to the AVM.

Pre-surgical embolization was attempted as the first step in treatment. Superselective angiography confirmed that both arteries fed the AVM and that the second vessel did continue to supply normal brain. This second vessel could not be safely embolized and the patient went to surgery for resection. Post-operative MR and angiography have confirmed complete resection of the AVM and the patient has been seizure free for thirty months.

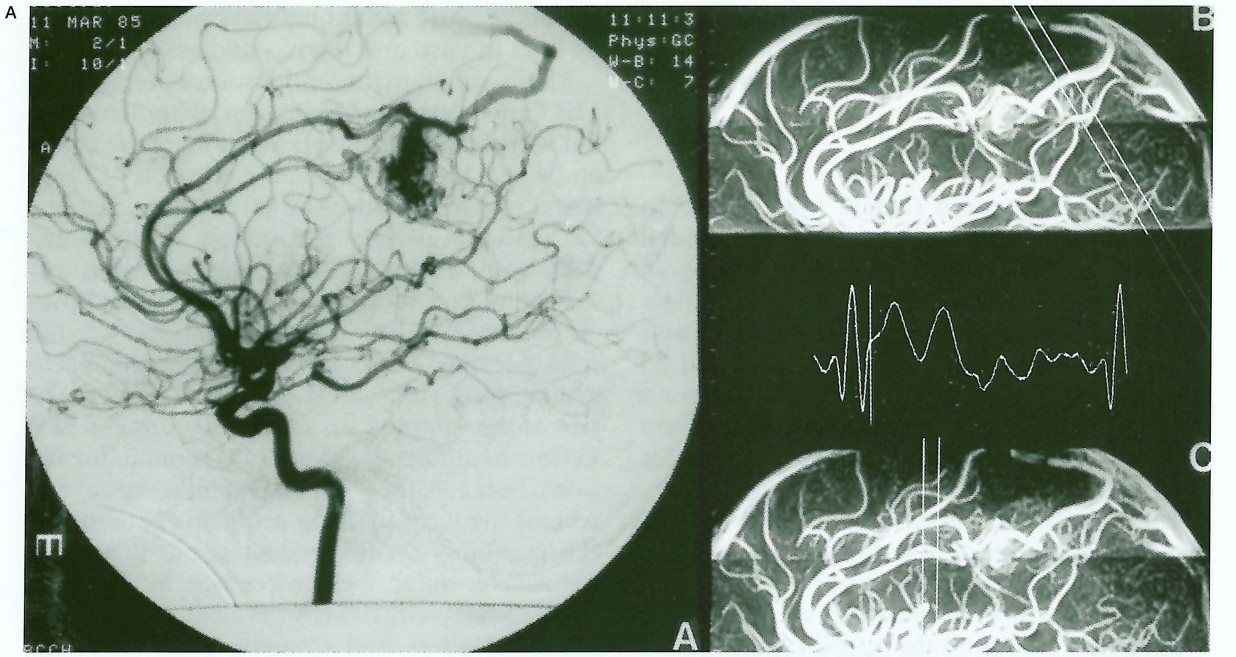
Patient 4:

A fifteen-year-old male presented with facial asymmetry and a bruit. The first MR of the face failed to establish a diagnosis, but a subsequent angiogram showed a right sided facial arterial venous fistula fed by multiple external carotid artery branches with venous drainage into the right internal jugular vein. We attempted to calculate the size of the shunt prior to embolization using MR Q flow.

The initial localizing MRA failed to show the vascular lesion because a standard walking saturation band placed above the sample slices eliminated the venous component of the fistula. By removing the saturation band we were able to identify the lesion, but the combined MRA/MRV also indicated that the patient exclusively used the right jugular foramen and internal jugular vein for intracranial venous outflow. Sampling of the venous outflow was straightforward, but because of the multiplicity of arterial feeders the arterial component was more complex. We assumed that the difference between the right and left external carotid arteries might be a reasonable estimate of shunt flow and therefore selected an axial plane that allowed us to measure both the external and internal carotid arteries, vertebral arteries and jugular veins simultaneously. Velocity encodings of 50, 100 and 200 cm/s were used.

Venous flow was measured between 153 and 160 ml/min (+/- 5%) and was sampled proximal to the venous entry into the internal jugular vein. The arterial difference between the right and left external carotids was estimated between 146 and 150 ml/min (+/- 3%). Thus the values were between 2 and 8% of each other.

The patient's fistula was embolized and the angiogram confirmed the intracranial venous drainage pathway isolated to the right. It was the impression of the treating radiologist that he had not completely closed all fistulae con-



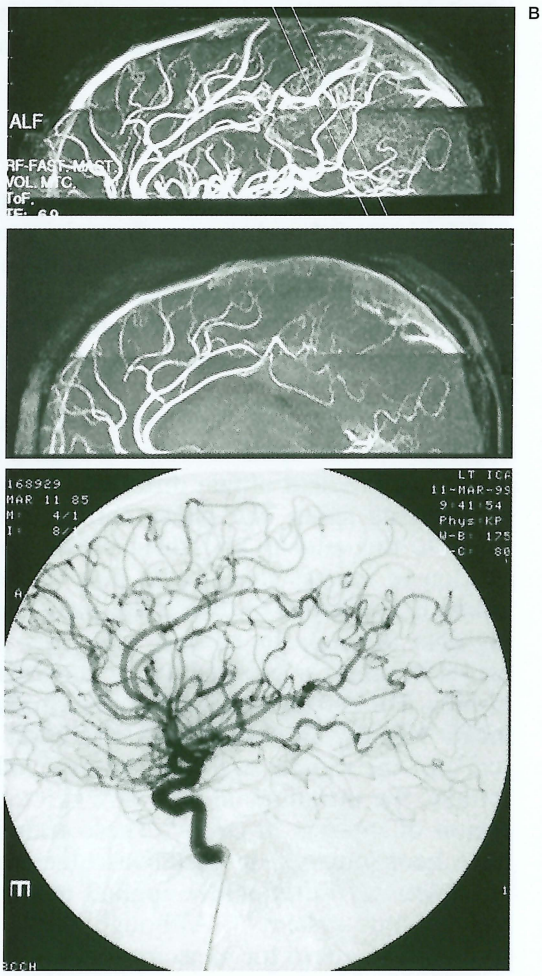


Figure 2 A) The left image is a lateral DSA view from patient 2. The right sided images are the corresponding MRA views used to place volumes for MR Q flow evaluation of both the venous and arterial components. Note the double feeding arteries and single draining vein. The double arterial flow was estimated at 146 ml/min, or 96% of the calculated venous outflow of 152 ml/min. The MR Q flow study was performed three months after stereotactic radiosurgery and did not show any post treatment change in flow but at 8 months showed a venous flow of 20 ml/min and almost no flow at 1 year and no flow at 2 years. B) The upper image correlates to that in A above, but is done 8 months after radiosurgery and, although the vein looks the same, the flow was now only 20 ml/min. The middle image is from the 2 year MR Q flow study which showed no vein and thus no venous flow could be measured. The lower image is a lateral DSA performed a little more than one month later (26 months post radiosurgery). This shows elimination of the AVM as predicted by the images and flow studies together.

tributing to the lesion, but the bruit was not audible after treatment. The patient has not undergone a follow up angiogram. A repeat MR study was performed nine months after treatment and MR Q flow studies suggested there was a persistent flow of 35-41 ml/min (+/- 15%) through the fistula site although the arterial difference between right and left external carotid arteries was measured between 12 and 16 ml/min (+/- 25%). The background phase errors were less than 5 ml/min, but this represents up to 30% of the suspected flow. We are uncer-

tain whether the venous flow measurement includes some normal facial venous drainage and is therefore higher than the calculated arterial difference.

Patient 5:

A fourteen-year-old female presented with headaches and imaging demonstrated a medial occipital lobe AVM with a nidus measuring >3 cm. Diagnostic angiography outlined multiple small posterior cerebral artery feeding vessels and a dominant single draining vein. MR Q flow was attempted and measured the venous flow at 110 ml/min, but was unable to measure the arterial component because of the complex architecture and myriad of small vessels.

The patient has been treated with partial glue embolization and radio-surgery and has not yet reached the end point of her treatment follow up. We are restricted to measuring the venous flow similar to the approach taken with Vein of Galen malformations. (This patient is scheduled for follow-up study in the next few weeks. These data can be added to the manuscript when available).

Discussion

The concept of being able to objectively measure arterial and venous flows in vascular malformations is appealing and the cases above outline the potential to do this using MR techniques. However the critical issue to be addressed is whether the data is accurate and reproducible.

Phase contrast MR angiography utilizes the observation that spins moving through a magnetic field gradient obtain different phase than non-moving spins. The phase shift is proportional to the velocity and, thus, allows the production of images sensitive to flow [5-8]. Cardiac gating is employed to divide the phase encoding data through the cardiac cycle into increments in either a prospective or retrospective fashion. For through plane flow, the product of mean velocity in (cm/s) and the pixel area (cm^2) of the sample region of interest, will determine the intraluminal bulk flow through the region of interest in cm^3/s [9]. These techniques have been pursued in cardiovascular imaging but relatively infrequently applied to the central nervous system [9,10]. Although there is no true gold standard for measuring blood flow in vessels, the MR techniques have been validated by both in vitro and in vivo studies [5-13].

There are many potential sources of error in MR Q flow such as; aliasing, misalignment, partial volume effects, misregistration, phase shifts, and signal loss [7,9,10]. Detailed discussion of these issues can be found elsewhere, but we believe the selection of scan parameters we have utilized (table 1) address most of these issues [14].

Factors that influence the accuracy and precision of MR Q flow measurements include the field of view, temporal resolution, the background pixel value, ROI selection as well as the size of the sampled vessel. We first applied MR Q flow to infants with Vein of Galen malformations because the draining vein is large and technically easy to sample. Having established the feasibility of the technique and generated believable data, we proceeded to measure flows in selected AVMs where both the smaller arterial feeders and draining veins could be sampled. We have documented an agreement between arterial and venous flows within 5-10% and this supports our belief that flow measurements in smaller arteries can be performed accurately. This is also supported by the work of H. Arheden et al [15] who concluded such segmented sequences give surprisingly accurate results in small vessels.

In very small vessels gated MR phase contrast angiography will underestimate the true velocity of intraluminal flow because of partial volume effects but the flow measurements can still be correct. The method of flow calculation may be valid because the average velocity is summed up over a greater area than the true lumen of the vessel. Thus, if the velocities outside the vessel have a true background correction value of zero, the product of the cross-sectional area in the lower calculated velocity will result in a true flow measurement over time [16,17]. This depends on accurate background correction and choice of region of interest.

Flow values are highly dependent on the background pixel values being correctly assigned to a value of zero since this enables a generous region of interest to encompass all of the flow from the vessel whether it is displaced or misaligned [7,11]. Background phase errors may be caused by many factors including susceptibility effects, microcirculation effects, and MR design limitations such as RF instability, gradient repeatability, echo centering, or echo sam-

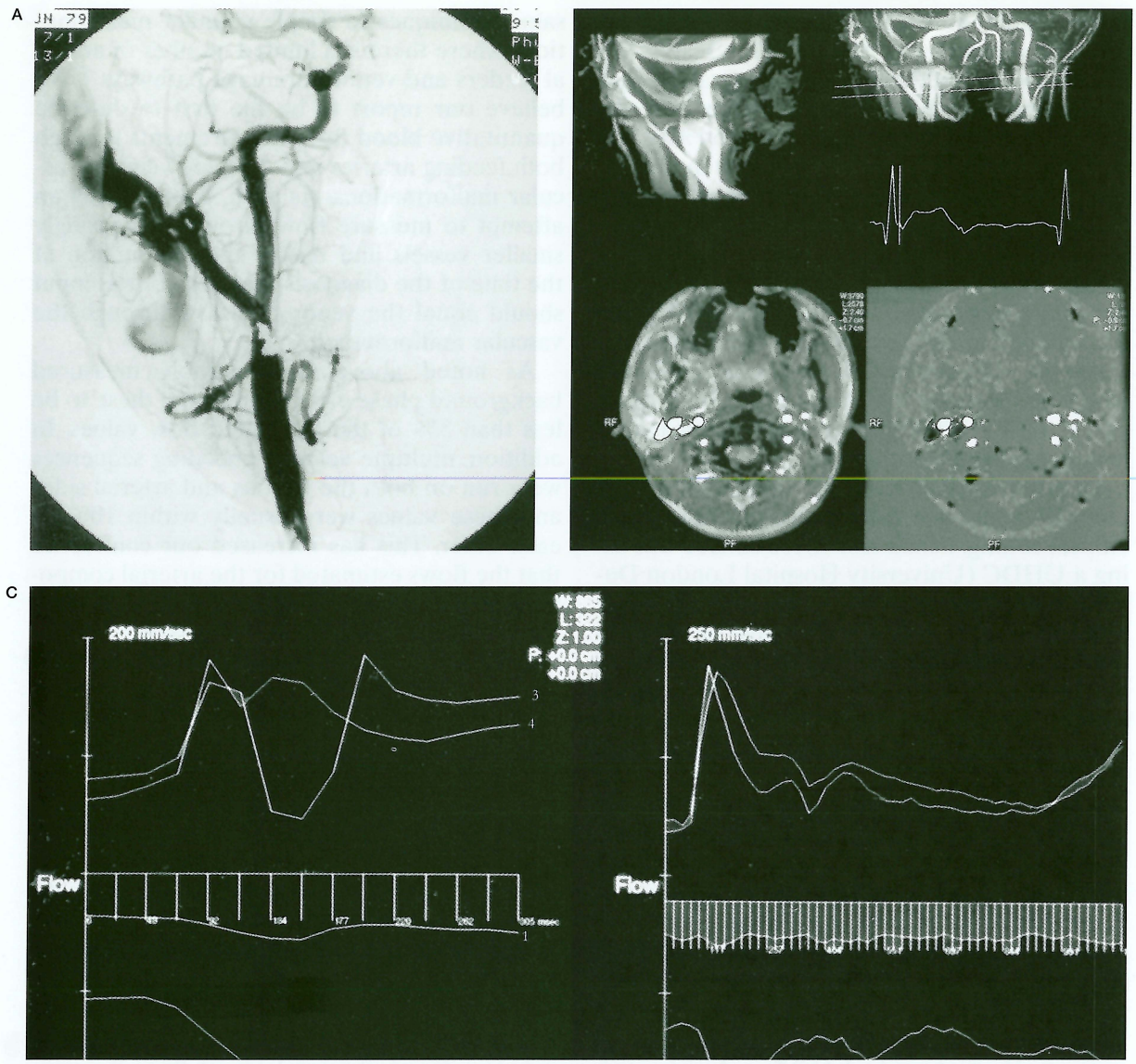


Figure 3 A) DSA study showing the A-V fistula in patient 4. See the enlarged external carotid system and abnormal, early drainage into an enlarged superficial venous system. Correlate with B below. B) The upper left image correlates well with A the DSA seen in A above. The upper right image shows the placed sample volume used to estimate MR Q flow. Note the placement allows for assessment of both ECA's, ICA's, and vertebral arteries as well as the single right sided internal jugular vein and abnormal superficial venous drainage of the A-V fistula. The lower images are the magnitude and flow images showing the axial relationship of the sampled vessels. Labeled volumes include: #1 A-V fistula venous outflow, #2 internal jugular vein, #3 ICA, and #4 ECA. C) The flows from B above are displayed here. On the left, there is aliasing of the arterial data because of low velocity encoded sequence. This is corrected on the right with higher velocity sensitivity. The A-V fistula venous flow was calculated at 153 ml/min. Arterial flow was estimated by taking the difference in flow between the right and left ECA's, which was 2.5 ml/s (150 ml/min), or 98% of the venous outflow.

pling[7]. In general, the background phase errors are less serious in the brain than in the chest because the lack of signal and random noise in the lungs translates into a greater challenge to find a background value of zero than occurs from the signal in the brain. If the background phase errors are large, then the measured values from the MR Q flow studies cannot be trusted. In all our cases background phase errors were substantially less than 5% of the calculated flow values.

Differences in flow rates have been reported

to be as great as 8 - 24% due to intra-observer variability in choosing regions of interest [6,11]. We have chosen a method of ROI generation that consists of using the magnitude images and setting the window width and levels at 50% of the maximal intraluminal signal intensity in the image. The images are magnified approximately four-fold which permits easier manual tracing of the ROI. Although the background phase errors were minimal in our series, flow estimates are more accurate with regions of interest tailored to the size of the true lumen because the obliquity of flow and noise within the image will increase with large ROIs. Both noise and partial volume effects are non-linear and may cause significant errors.

In order to determine the inherent error of our MR technique prior to employing it in a clinical setting, bench tests were carried out using a UHDC (University Hospital London Development Corporation, London, Canada) flow phantom that could create a range of continuous and pulsatile flows [3]. The data was analyzed with a cardiac software package by two radiologists who were unaware of what flow rates had been selected and the results were compared to the known answer. A similar approach was also used employing an ECMO (extra-corporeal membrane oxygenation) pump normally used for cardiac bypass. As reported previously from these tests, calculated flow values were found to be within 10% of the true values.

In Neuroradiology these techniques have been used to measure blood flow in the carotid and basilar arteries in order to assess total cerebral blood flow. Marks, et al [18] reported on 40 patients, 16 of whom had AVMs and had significantly higher flow rates in the carotid and basilar arteries. Flow rates increased in all three arteries with increasing AVM volume and they also reported that the four AVM's that underwent partial embolization demonstrated a corresponding decrease in total cerebral blood flow. However, in this report, the anterior and posterior cerebral arteries were found to be too small for reliable measurements.

Our initial work focussed on measuring venous flow from vein of Galen vascular malformations because the venous outflow was large and less susceptible to the limitations of the MR technique [3]. Having established the reliability and reproducibility of the data across patients and time, we have attempted to apply the same techniques to simple vascular malformations where there is a limited number of arterial feeders and venous drainage pathways [13]. We believe our report to be the first to describe quantitative blood flow measurements through both feeding arteries and draining veins of vascular malformations. As such, it represents an attempt to measure flow through increasingly smaller vessels and makes the assumption at the time of the diagnosis that the arterial input should equal the venous outflow through the vascular malformation.

As noted above, we routinely measured background phase errors and found these to be less than 5% of the calculated flow values. In addition, multiple velocity encoding sequences were run on both the venous and arterial sides and these values were usually within 10% of each other. This has increased our confidence that the flows estimated for the arterial component of the vascular malformations have been reasonable estimates of vascular flow.

Initially as shown in case 1, we obtained MR Q flow values in vein of Galen malformations with a venous outflow greater than 10 mm in diameter. After seeing reliable correlation between the MR Q flow studies and the angiographic results of embolization, we attempted to sample flow values and blood vessels smaller than 5 mm in diameter. Tang, et al [19] have reported that at least 16 voxels must cover the cross-section of a vessel lumen to achieve a measurement accuracy within 10% and, according to table 3, we have not achieved this benchmark. However, we believe that although the peak velocities may be affected by partial volume effects, the total blood flow measurements have been relatively unaffected as demonstrated by the reproducibility and a general agreement with the venous outflow measurements.

The application of cardiac gated phase contrast MR angiography on progressively smaller arterial and venous feeders is demonstrated in cases 2-5. Case 2 demonstrates the progressive, sequential reduction in flow through a vascular malformation after radiosurgery. Even when the MR angiogram by visual inspection failed to demonstrate a significant difference in appearance, the MR flow values indicated there had been a dramatic reduction in flow that corresponded to the appearance of cerebral edema surrounding the nidus. The venous flow re-

duction in this case was an accurate representation of the involution of the lesion with good correlation with the final diagnostic angiogram. As outlined in figure A, flow seemed to decrease in an exponential manner after radiosurgery. This suggests that MR Q flow can provide information on the natural history of nidal obliteration after radiosurgery and may be able to identify, earlier than two years after treatment, the twenty per cent of patients who will fail therapy.

However, in case two the arterial flow rates maintained their initial measured values despite our expectation that the arterial flow rates should have diminished. Whether this represents a steal component of the arterial venous malformation or our inability to accurately sample close to the nidus is uncertain, but does suggest that venous outflow if it is selectively from the AVM may be a more accurate measure of AVM flow reduction.

In case 3 the MR flow data showed superb congruence between the arterial and venous flow. The first arterial feeder accounted for only 60% of the measured venous flow, while both arteries contributed between 104-108% of the venous flow, explaining why the angiogram demonstrated flow through the nidus to normal brain. Thus the MR data persuasively argued that both arteries must feed the patient's AVM despite the initial angiographic interpretation. This conclusion was confirmed by subsequent superselective angiography. Case 4 also outlines how the MR data contributed to the identification of isolated right sided intracranial venous outflow that could have been compromised by inadvertent occlusion of the right internal jugular vein at the time of embolization. Thus MR flow studies contributed to the understanding of patient's vascular malformation and anatomy as well as being a robust technique for following treatment effects.

Cases 1,3 and 4 also have used the assumption that differences in arterial and venous flows may be used to infer certain conclusions. In the VGAM patients we have used the difference between cardiac output and VGAM venous flow to estimate the amount of shunting. In case 4 we assumed that the difference between the external carotid artery flows should reflect the amount of shunting venous blood, but this is a questionable assumption. It is also possible the entire right external carotid bed may see increased flow or that there is a normal minor asymmetry between sides of the face. However the data was within 10% of the measured venous flow.

Case 5 was included to demonstrate that many AVMs are not amenable to arterial and venous sampling. In simple AVMs with few arterial feeders and a simple pathway of venous drainage the MR Q flow techniques may be applied in less than 20 minutes as part of a routine MR study. However if the vascular pathways are complex, the need to sample perpendicular to each vessel lumen results in an impractical or impossible technique. Nonetheless, we have encountered 17 AVMs over the past five years and have been able to extract believable venous data in eight and arterial data in five. Thus a significant number of AVMs may be followed by MR flow measurements.

We acknowledge that this is a small group of patients and the results may not be applicable to the wider population. There are inherent technical difficulties with assessing flow through multiple arterial feeders or draining veins, so the technique is most easily applied to AVMs with simple, easily defined feeding arteries or draining veins. Nonetheless, this technique is relatively straightforward to learn, rapid, cost-effective and may provide an objective means to assess therapeutic maneuvers when applied to head and neck vascular malformations.

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